Toward a Human-like Biped Robot with Compliant Legs

Fumiya Iida [a,b,1], Yohei Minekawa [a] Juergen Rummel [a] and Andre Seyfarth [a]
[a] *Locomotion Laboratory, University of Jena, Germany*
[b] *Artificial Intelligence Laboratory, University of Zurich, Switzerland*

Abstract. Conventional models of bipedal walking generally assume rigid body structures, while elastic material properties seem to play an essential role in nature. On the basis of a novel theoretical model of bipedal walking, this paper investigates a model of biped robot which makes use of minimum control and elastic passive joints inspired from the structures of biological systems. The model is evaluated in simulation and a physical robotic platform with respect to the kinematics and the ground reaction force. The experimental results show that the behavior of this simple locomotion model shows a considerable similarity to that of human walking.

Keywords. Legged Locomotion, Biped Walking, Passive Dynamic Walking

1. Introduction

In the fields of biomechanics and robotics, bipedal walking has been investigated for our further understanding of versatile locomotion mechanisms of human and robots. Based on the biomechanical investigations, a few different approaches were previously proposed. Bipedal locomotion in artificial systems was firstly engineered by using predetermined trajectories of the leg joints (e.g. [1]). Although this approach demonstrated an outstanding versatility in locomotion behaviors, adaptivity is highly restricted because this approach requires a precise environment model and demanding computational duty for calculating the trajectories.

Research of Passive Dynamic Walking has questioned the conventional approach. On the basis of biomechanical models, the so-called “compass gait model" or “ballistic walking model"[2], a number of Passive Dynamic Walkers (PDWs) have been developed and demonstrated natural walking behavior (e.g. [3,4,5,6]). Inspired by the muscle activities in the swing leg during human walking, these models utilize no actuation and purely mechanical pendulum dynamics are used to achieve walking behavior.

More recently, a theoretical model, the so-called “spring-mass walking" has been proposed, which demonstrated a walking dynamics with a considerable similarity to that of human [7]. Although the spring-mass model was originally proposed for running behavior [8,9,10], an extension of the original model can be applied for walking behavior,

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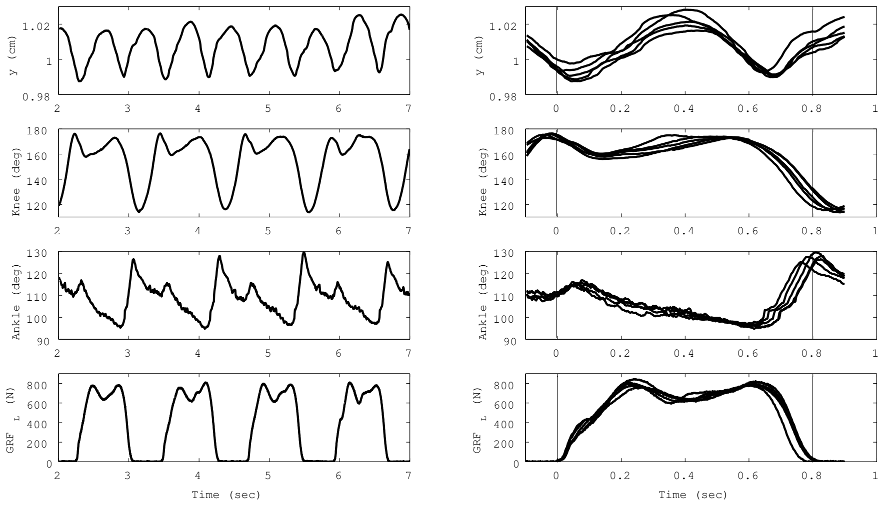
[1] Correspondence to: Fumiya Iida, Andreasstrasse 15, CH-8057 Zurich, Switzerland. Tel.: +41 44 635 4354; Fax: +41 44 635 4507; E-mail: iida@ifi.unizh.ch.



(a) (b)

Figure 1. Behavior of human walking. Vertical movement of the body (Top figure), angular trajectories of knee and ankle joints (Middle figures), and vertical ground reaction forces (Bottom figure) are shown over time-series 4 leg steps (a) and the data aligned with respect to the ground reaction force (b). Vertical lines in Figure (b) denotes the moment when the swing and stance phases are switched.

which leads to our further understanding of underlying mechanisms of human locomotion.

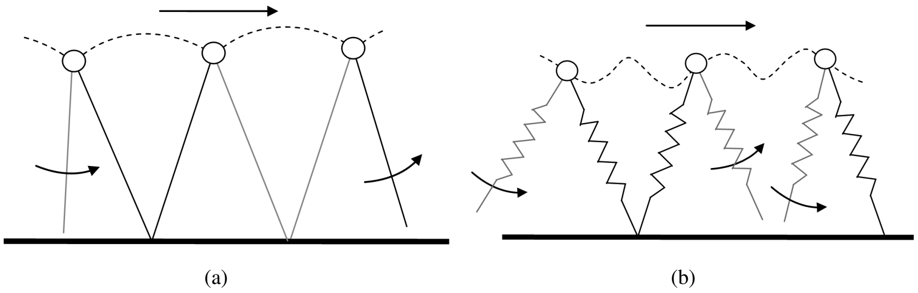
Based on this novel theoretical model, the goal of this paper is to explore a mechanically realistic model of human-like bipedal walking, which can actually be implemented to a robotic platform. With a simple motor control scheme, we analyze how the morphological properties of the leg design can be used for dynamic bipedal locomotion behavior, and compare the behavior of the system with human locomotion.

The structure of this paper is as follows. First, we briefly introduce the walking behavior of a human and the spring mass walking model. Then we propose a new locomotion model and test it in simulation and in a robotic platform.

2. Bipedal Walking with Compliant Legs

2.1. Bipedal Walking of Human

In order to understand the influence of compliant legs during walking behavior, we firstly investigate the walking behavior of a human subject. In this experiment, we use a treadmill with a set of motion capture system (6 Qualisys motion capture units; sampling frequency of 240 Hz) and force plates (Kistler 9281B11; sampling frequency of 1000 Hz), with which we analyze the kinematics of human behavior as well as the ground reaction force.


(a)

(b)

Figure 2. (a) Compass gait model and (b) Spring mass walking model. The dashed lines represent the different body excursion in these models.

A human subject was asked to walk on a treadmill at a constant speed of 1 m/sec for 20 seconds. The kinematics and the ground reaction force were analyzed, and we found that there are a few unique aspects of human walking that cannot be explained by the compass gait model as shown in Figure 1. Firstly, there is a significant difference in the vertical movement of the body. While the compass gait model shows the circular trajectory of the body movement around the foot ground contact during a stance phase, the human body excursion is generally more complicated; Vertical position of the body decreases at the beginning of the stance phase, and it increases and decreases; And toward the end of the stance phase, it starts increasing again. An advantage of this movement of the body could be that it has less displacement of vertical oscillation of the body. Secondly, behavior of a knee joint during stance phase is also more complicated than that of the compass gait model; At the beginning of stance phase, the knee angle firstly decreases before a large peak. A possible advantage of the first decrease is that the knee joint could absorb the impact force at the touch-down. Thirdly, the ankle joint shows also a complex behavior although the compass gait model has no ankle joint; There is a small peak at the beginning, and it increases toward the end of stance phase. Finally, the ground reaction force generally shows a M-shape, whereas the compass gait model generally shows a single peak.

2.2. *Spring Mass Model for Walking*

The spring mass model was originally proposed for characterizing running behavior of animals [8,9,10]. The model consists of a body represented as a point mass and a leg approximated by a linear spring. This extremely simple theoretical model has explained a number of eminent features of running behavior in animals including humans'. Recently, this model was extended for walking behavior, which explained a few aspects of human bipedal locomotion including the complex dynamics introduced in the previous subsection [7].

Although the spring mass model for walking shows a significant plausibility as a walking model of human, this theoretical model has to be elaborated for robotic implementation. In the rest of this paper, we explore a mechanically realistic model considering the theoretical spring-mass walking model and the anatomical structure of biological systems.

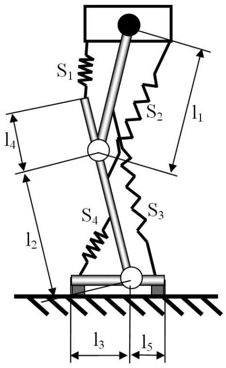


Figure 3. Simulation model of a biped robot. Only one of the two legs is shown in this figure. The model consists of a joint controlled by a motor (represented by a black circle) and three leg segments which are connected through two passive joints (white circles). Two ground contact points are defined in the foot body segment.

Table 1. Specification of the robot.
∗Spring constants are dimentionless.

Param.	Description	Value
l_1	Thigh	10 cm
l_2	Shank	10 cm
l_3	Foot	4 cm
l_4	Spring Attach.	2 cm
l_5	Heel	2 cm
S_1	Spring const.	100
S_2	Spring const.	200
S_3	Spring const.	800
S_4	Spring const.	450
M	Total mass	950g

2.3. Model of a Biped Robot

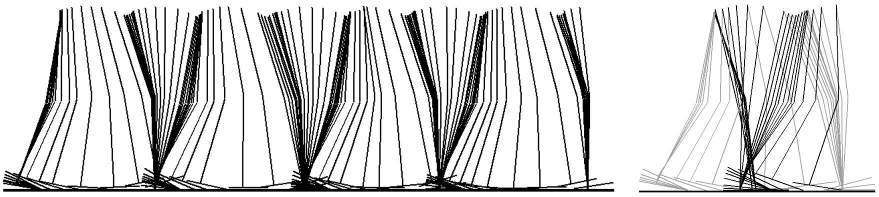
Figure 3 shows the simulation model of a biped robot investigated in this paper. This model consists of 7 body segments, two motors at hip joints with position control, four passive joints in the knee and ankle joints, and 8 linear springs. The springs are implemented as the substitutes for the muscle-tendon systems, which constrain the passive joints. A unique feature of this robot is that 6 of the springs are connected over two joints, which are known as the so-called biarticular muscles in the biological systems (i.e. 4 springs attached between the hip and the shank, 2 are between the thigh and the heel). For the sake of real-world implementation in a robotic platform, the dimension of this model is scaled down as shown in Table 1. There are two ground contact points in a leg defined in this model. In the simulation, we test the model in a level ground surface with a physically realistic interaction model based on a biomechanical study [11]. The vertical ground reaction forces are approximated by nonlinear spring-damper interaction, and the horizontal forces are calculated by a sliding-stiction model. It switches between sliding and stiction when the velocity of the foot becomes lower or higher than the specified limit. We used 0.55 and 0.75 for the sliding and stiction friction coefficients, respectively.

For control of the motors, we employed a simple oscillation, in which the angular position of the hip joint is determined by the sinusoidal curve as follows:

$$P_r(t) = Asin(\omega t) + B \tag{1}$$

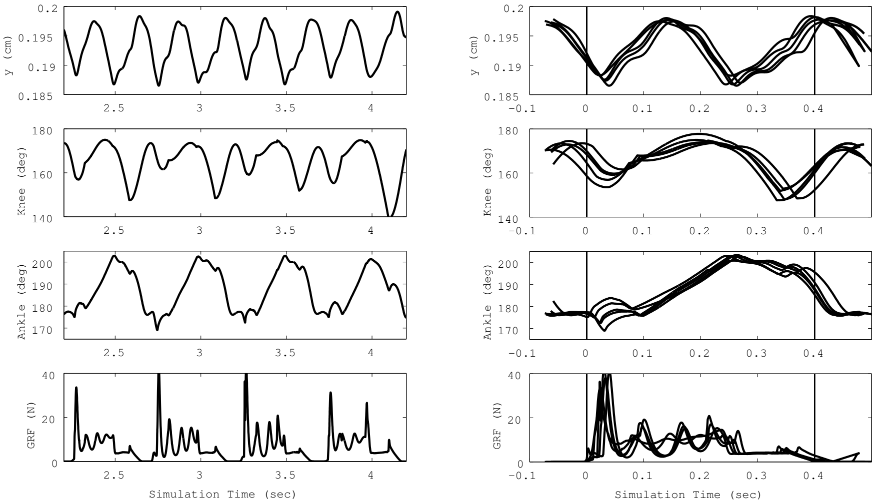
$$P_l(t) = Asin(\omega t + \pi) + B \tag{2}$$

where there are three parameters of amplitude A, frequency ω and offset B. By using this simple control scheme, we are able to evaluate how the morphological constraints can contribute to walking behavior. This model is implemented in a planar space for the



(a) (b)

Figure 4. Stick figures of the walking behavior in simulation. (a) The behavior of one leg during four leg steps, and (b) the behavior of two legs during a single step.



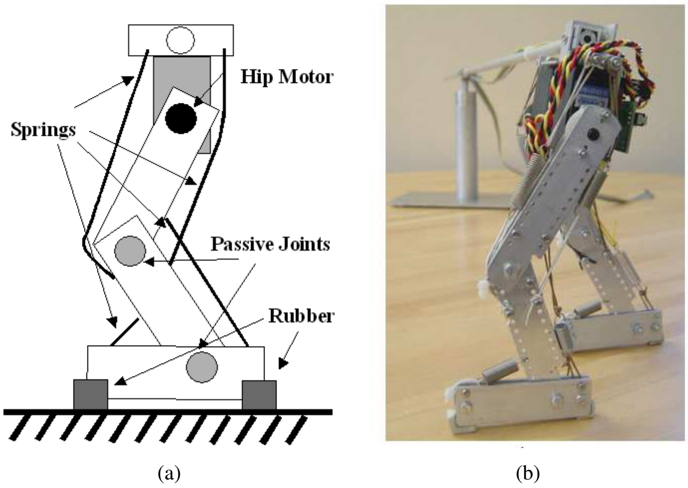
(a) (b)

Figure 5. Walking behavior of the simulated robot. Vertical movement of the body (Top figure), angular trajectories of knee and ankle joints (Middle figures), and vertical ground reaction forces (Bottom figure) are shown over 4 leg steps (a) and the data aligned with respect to the ground reaction force (b).

sake of simplicity, thus no rotational movement of the upper body (i.e. hip segment) is considered.

3. Experiments

This section explores dynamic locomotion behavior of the proposed model in the simulation and discusses how the model can be implemented in a robotic platform.



(a) (b)

Figure 6. (a) Schematics of the robot design, (b) photograph of the robot with the supporting rotational bar.

3.1. Simulation Result

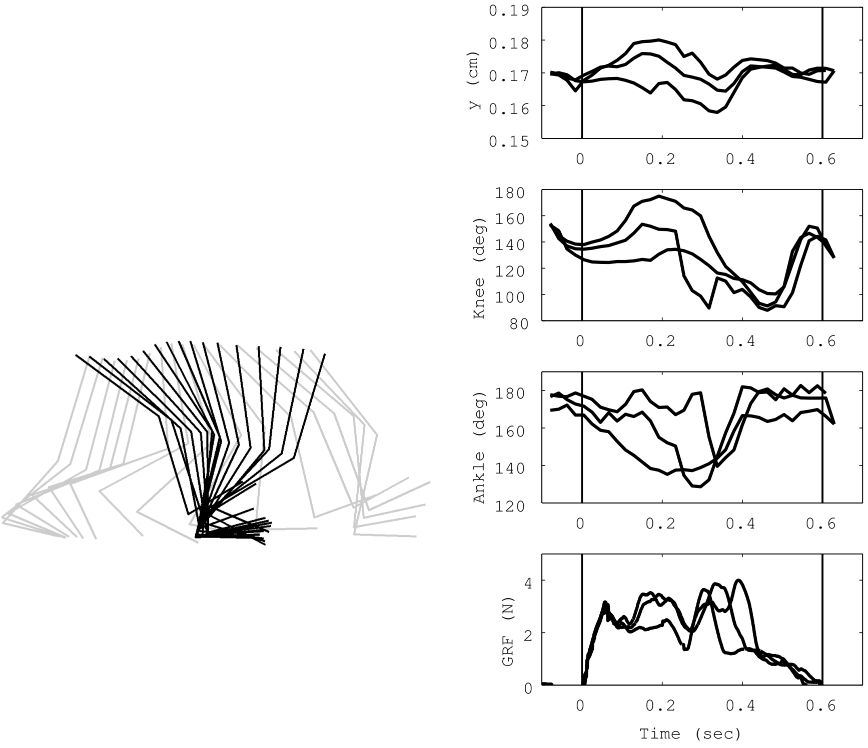
We constructed a simulation model of the proposed biped robot model in Mathworks Matlab 7.01 together with SimMechanics toolbox. In order to achieve biologically plausible locomotion behavior, we made use of hip-motor control parameters according to the walking behavior of human as follows: $A = 20$ degrees, $B = 5$ degrees, and $\omega = 2$ Hz. With these control and morphological parameters, the system exhibits relatively stable walking behavior. Even without any sensory feedback, the system exhibits a stable locomotion process regardless of initial conditions. Figure 4 shows a sequence of single leg movement during a few leg steps and the movement of two legs during one leg step.

There are a few points to be mentioned. Firstly, even without actuation, the natural movement of passive joints can be achieved due to the morphological constraints of segment length and elasticity. Secondly, the body (i.e. the upper end of the shank segment) shows a sinking movement at the beginning of stance phase because of the geometrical constraints of foot segment and the knee bending at the touch down.

These points are more clearly shown in Figure 5. The behavior of this simulation model resembles to the behavior of human locomotion explained in the previous section; Vertical rise of the body starts after the leg touch-down and before the leg lift-off; Significant knee flex at the beginning of stance phase; Extension of ankle joint toward the end of stance phase; Multiple peaks in the ground reaction force.

3.2. Robot Experiments

The simulation model is now implemented in a physical robot platform as shown in Figure 6. This robot consists of passive joints in knees and ankles, and two commercial servomotors (Conrad HS-9454) are used in the hip joints, as in the simulation model. We used four tension springs and rubber materials at the ground contact point in order to gain ground friction and to avoid impact force at touch-down. The same control parameters were used to conduct a set of experiments. Then behaviors were measured by both a



(a)

(b)

Figure 7. (a) Leg trajectory of the biped robot during one step. Black and gray lines depict right and left legs, respectively. (b)Body excursion, angular trajectories of the knee and the ankle joints and the ground reaction force of the robot during a few leg steps (aligned with respect to the ground reaction force).

standard motion capture system and a force plate (the same setup mentioned earlier) for the detailed analysis.

Figure 7(a) shows a stick figure of a typical locomotion behavior and more detailed trajectories are shown in Figure 7(b). Although the kinematics of the locomotion behavior is not as stable as that in simulation, we can clearly see the salient features of the proposed model (i.e. the body excursion, the knee flex at the beginning of the stance phase, and the multiple peaks in the ground reaction force).

4. Conclusion

This paper presented a novel control scheme of bipedal locomotion and a set of experimental results in simulation and a robotic platform. Compared to the conventional PDWs, it is shown that the dynamic behavior of the proposed model is significantly comparable to that of human, although it was tested only in planar environment (i.e. yaw, pitch, and rotation movement are fixed).

The significance of the achievement presented in this paper is twofold. Firstly, it is shown that biologically plausible walking dynamics can be achieved by using an extremely simple control if the leg design takes mechanical constraints into account. We expect that this model could help understanding some of the underlying mechanisms of human bipedal walking. Especially it would be interesting to explore further to what extent the behavior of the springs can be comparable to the muscle activities of a human during walking. According to a prosthetic research, such a leg design as proposed in this paper seems to play a significant role in human walking [12].

Secondly, the approach utilizing compliant properties in the leg can be extended to running behavior, as previously demonstrated by the spring-mass model. It would be particularly interesting to extend the same leg design for both walking and running behaviors. The transition between both gaits can also be investigated along the same line of research by using the proposed model.

Acknowledgements

This research is supported by the German Research Foundation (DFG, SE1042) and the Swiss National Science Foundation (Grant No. 200021-109210/1).

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